Proton capture reaction cross section measurements on ^{162}Er for the astrophysical γ-process

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TM

MTA atomki DEBRECEN

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50 Jahre Institut für Kernphysik Universität zu Köln

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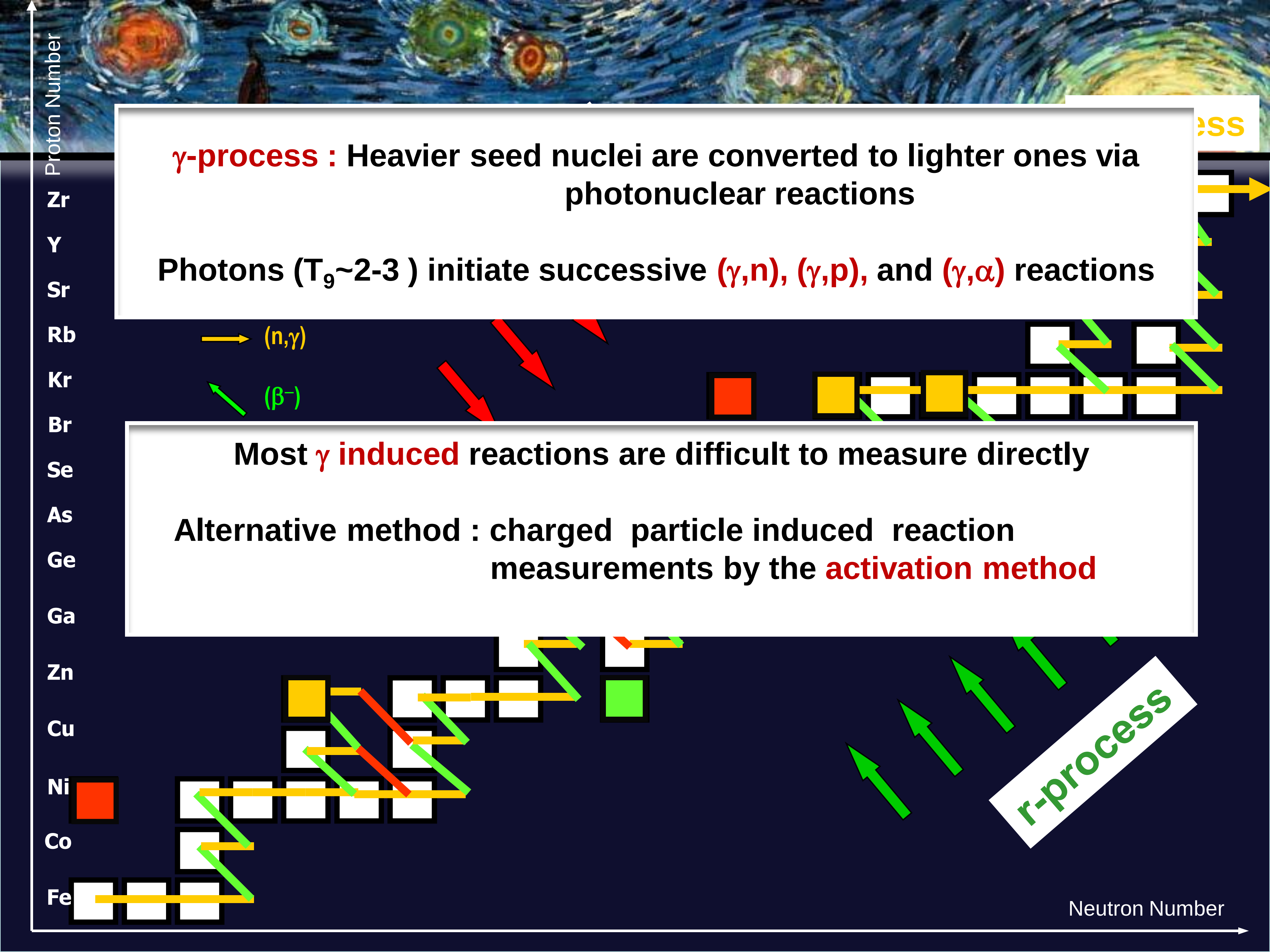
- Nucleosynthesis
  - Big Bang
    upto Li and Be
  - A<60
    fusion reactions
  - A>60
    processes
    - s-process
    - r-process
    - **p-process**

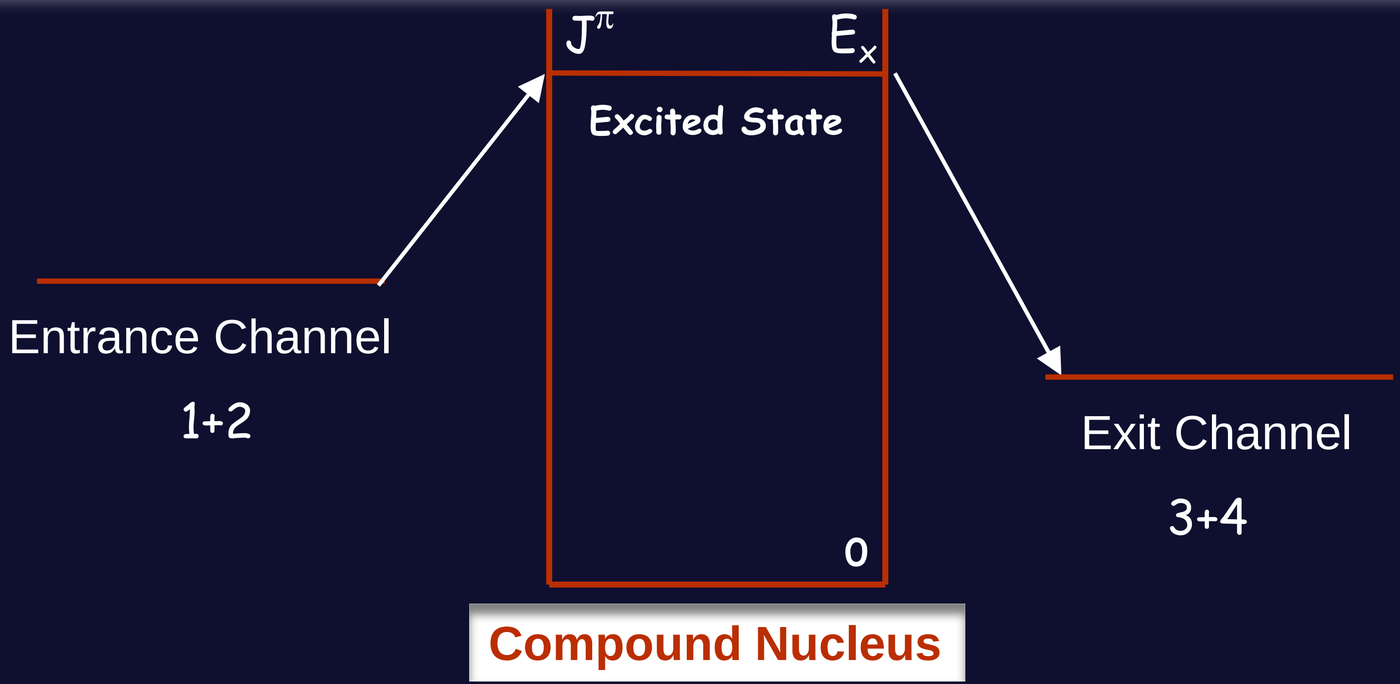
γ-process : **Heavier seed nuclei are converted to lighter ones via photonuclear reactions**

Photons (T_9~2-3) initiate successive (γ,n), (γ,p), and (γ,α) reactions

Most γ induced reactions are difficult to measure directly

Alternative method : charged particle induced reaction measurements by the activation method





Reaction : 1 + 2 ⟶ C ⟶ 3 + 4 + Q (>0)

$$\sigma_{12} = \pi \lambda_{12}^2 \frac{2J+1}{(2J_1+1)(2J_2+1)}(1+\delta_{12})\left|\langle 3+4|H_{II}|C\rangle\langle C|H_I|1+2\rangle\right|^2$$

$$\sigma_{34} = \pi \lambda_{34}^2 \frac{2J+1}{(2J_3+1)(2J_4+1)}(1+\delta_{34})\left|\langle 1+2|H_I|C\rangle\langle C|H_{II}|3+4\rangle\right|^2$$

$$\frac{\sigma_{12}}{\sigma_{34}} = \frac{m_3 m_4 E_{34}(2J_3+1)(2J_4+1)(1+\delta_{12})}{m_1 m_2 E_{12}(2J_1+1)(2J_2+1)(1+\delta_{34})}$$

By measuring σ_{12} ⟶ σ_{34} can be calculated

(time-reversal invariance theorem)

Reaction Rate $\langle\sigma v\rangle$

$$\langle\sigma v\rangle_{12} = \left(\frac{8}{\pi\mu_{12}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma_{12} E_{12} \exp\left(-\frac{E_{12}}{kT}\right) dE_{12}$$

Entrance Channel

$$\langle\sigma v\rangle_{34} = \left(\frac{8}{\pi\mu_{34}}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma_{34} E_{34} \exp\left(-\frac{E_{34}}{kT}\right) dE_{34}$$

Exit Channel (inverse reaction)

$$\frac{\langle\sigma v\rangle_{34}}{\langle\sigma v\rangle_{12}} = \frac{(2J_1+1)(2J_2+1)(1+\delta_{34})}{(2J_3+1)(2J_4+1)(1+\delta_{12})} \left(\frac{\mu_{12}}{\mu_{34}}\right)^{3/2} \exp\left(-\frac{Q}{kT}\right)$$

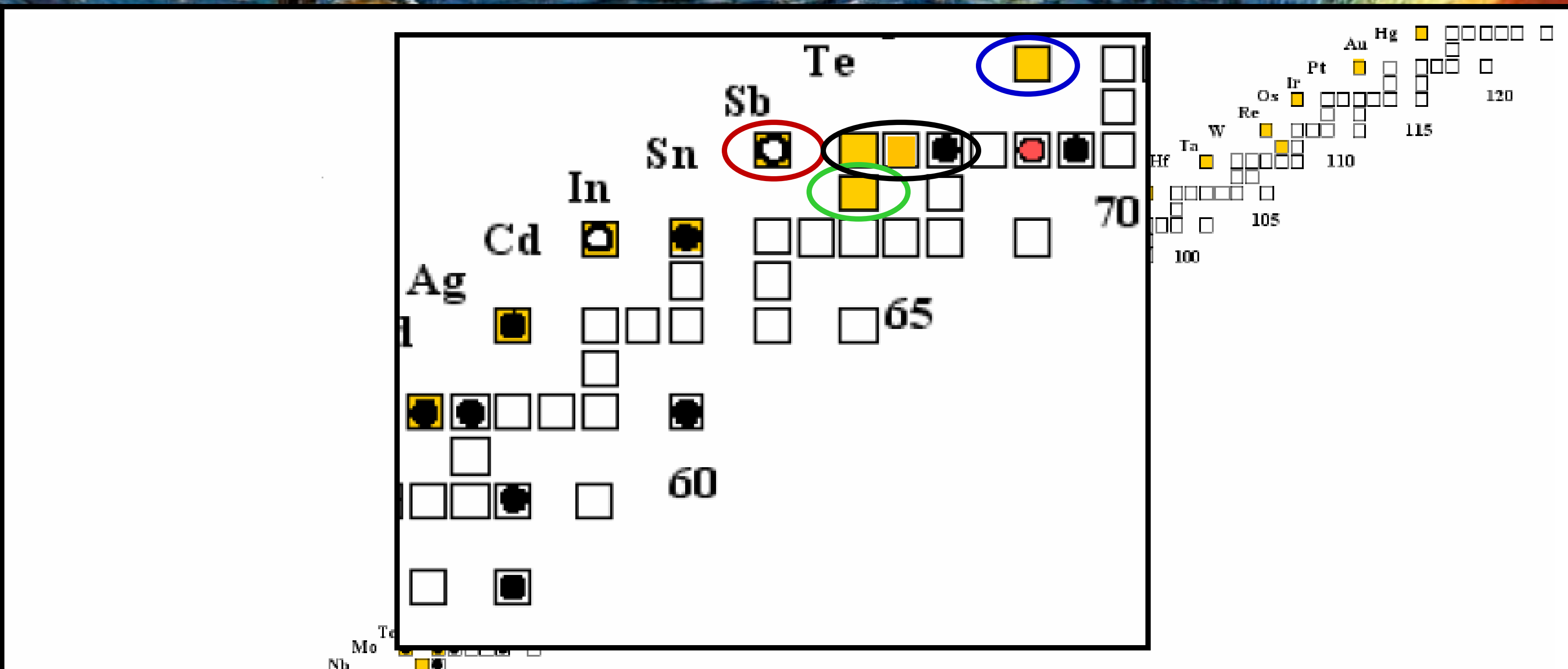
Net reaction rate:

$$r = r_{12} - r_{34} = \frac{N_1 N_2}{1+\delta_{12}} \langle\sigma\, v\rangle_{12} - \frac{N_3 N_4}{1+\delta_{34}} \langle\sigma\, v\rangle_{34}$$

$$r = \frac{\langle\sigma v\rangle_{12}}{1+\delta_{12}} \left[N_1 N_2 - N_3 N_4 \frac{(2J_1+1)(2J_2+1)}{(2J_3+1)(2J_4+1)} \left(\frac{\mu_{12}}{\mu_{34}}\right)^{3/2} \exp\left(-\frac{Q}{kT}\right) \right]$$

The modeling of p-process nucleosynthesis requires a large network of thousands of nuclear reactions involving stable and unstable nuclei.
The relevant astrophysical reaction rates derived from the reaction cross sections are necessary inputs to the p-process nucleosynthesis modeling.

P-process studies rely on the theory



$^{112}Sn(\alpha,\gamma)^{116}Te$ *N. Özkan et al., Phys. Rev. C **75**, 025801 (2007)*

$^{113}In(\alpha,\gamma)^{116}Sb$ *C. Yalçın et al., Physical Review C **79**, 065801 (2009)*

$^{120}Te(p,\gamma)^{121}I$ *R. T. Güray et al., Physical Review C **75**, 025801 (2009)*

$^{114,115,116}Sn(p,\gamma)^{115,116,117}Sb$ and $^{114,115}Sn(\alpha,\gamma)^{118,119,120}Te$

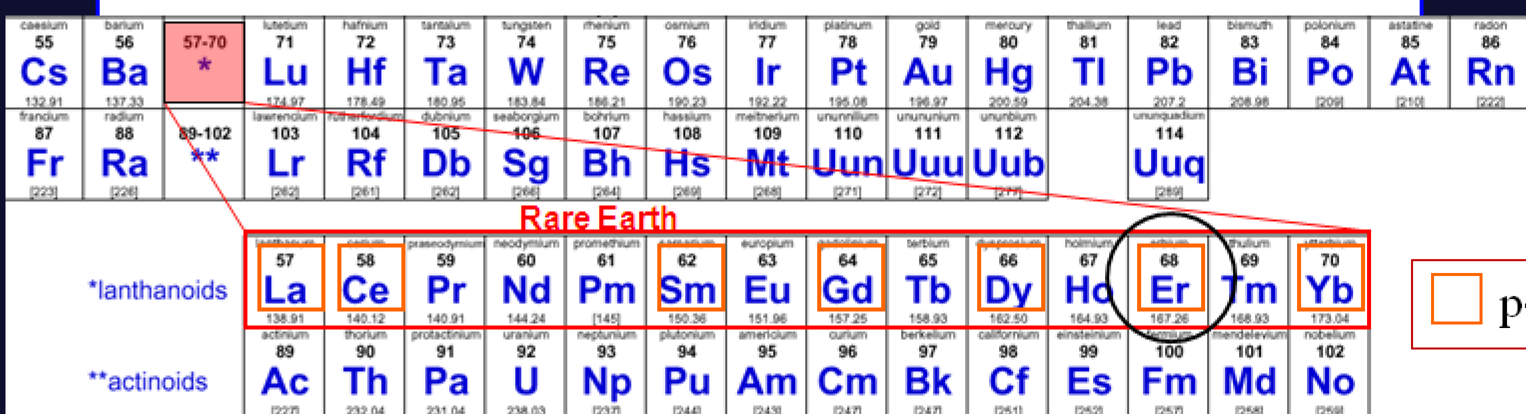
An excellent case for testing the reliability of the Hauser-Feshbach prediction near the closed proton shell *Z* = 50 *Analyses are under process*

List of p-nuclei with their solar and isotopic abundances

Nucleus	Abundance [Si = 10^6]	Isotopic abundance (%)	Nucleus	Abundance [Si = 10^6]	Isotopic abundance (%)
^{74}Se	0.55	0.88	^{132}Ba	0.00453	0.10
^{78}Kr	0.153	0.34	^{138}La	0.000409	0.09
^{84}Sr	0.132	0.56	^{136}Ce	0.00216	0.19
^{92}Mo	0.378	14.84	^{138}Ce	0.00284	0.25
^{94}Mo	0.236	9.25	^{144}Sm	0.008	3.10
^{96}Ru	0.103	5.52	^{152}Gd	0.00066	0.20
^{98}Ru	0.035	1.88	^{156}Dy	0.000221	0.06
^{102}Pd	0.0142	1.02	^{158}Dy	0.000378	0.10
^{106}Cd	0.0201	1.25	^{162}Er	0.000351	0.14
^{108}Cd	0.0143	0.89	^{164}Er	0.00404	1.61
^{113}In	0.0079	4.3	^{168}Yb	0.000322	0.13
^{112}Sn	0.0372	0.97	^{174}Hf	0.000249	0.16
^{114}Sn	0.0252	0.66	^{180}Ta	$2.48 \cdot 10^{-6}$	0.01
^{115}Sn	0.0129	0.34	^{180}W	0.000173	0.13
^{120}Te	0.0043	0.09	^{184}Os	0.000122	0.02
^{124}Xe	0.00571	0.12	^{190}Pt	0.00017	0.01
^{126}Xe	0.00509	0.11	^{196}Hg	0.00052	0.15
^{130}Ba	0.00476	0.11			

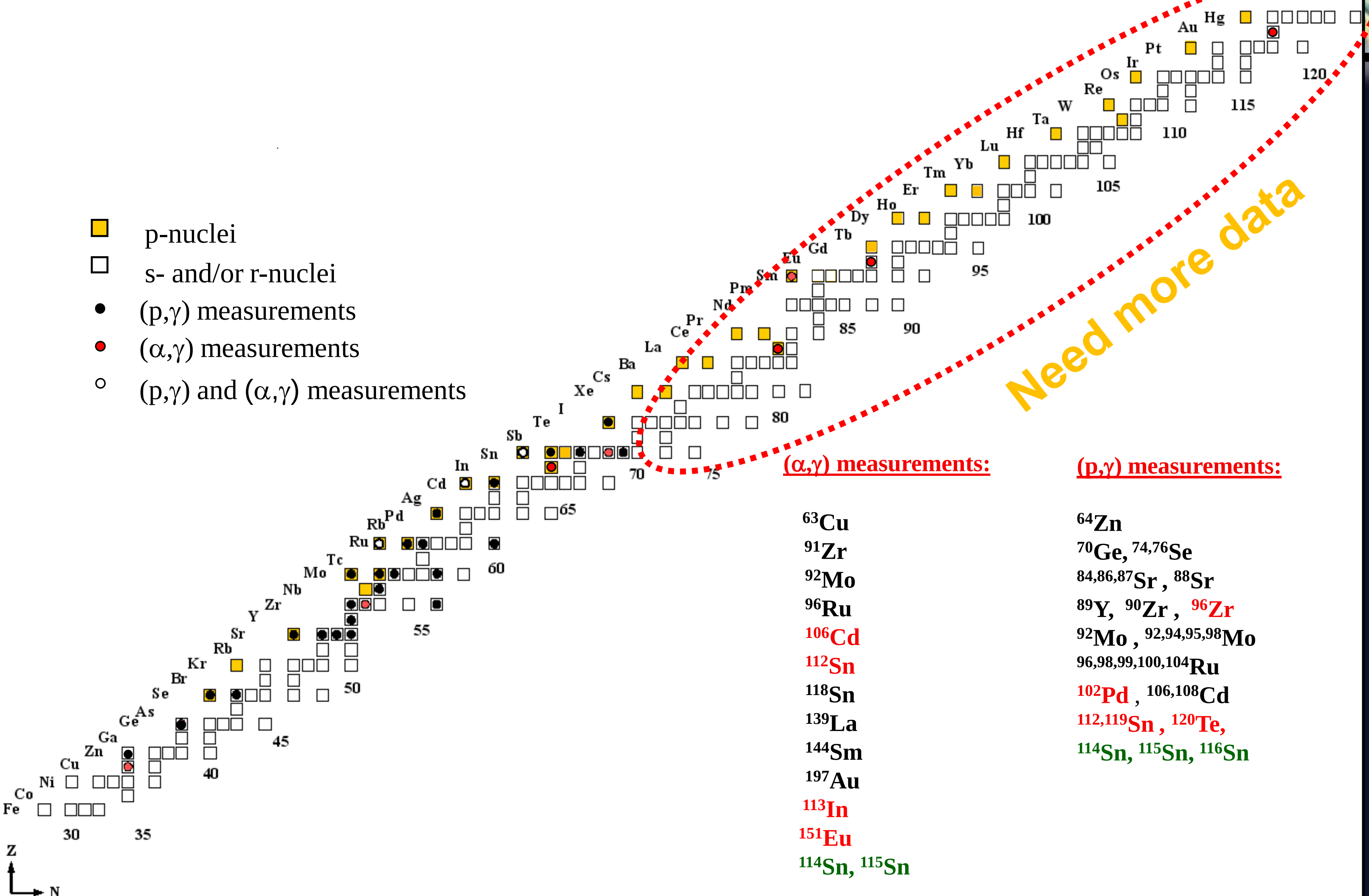
done

Good candidates



p-nuclei

Experimental measurements by activation method



(α,γ) measurements:

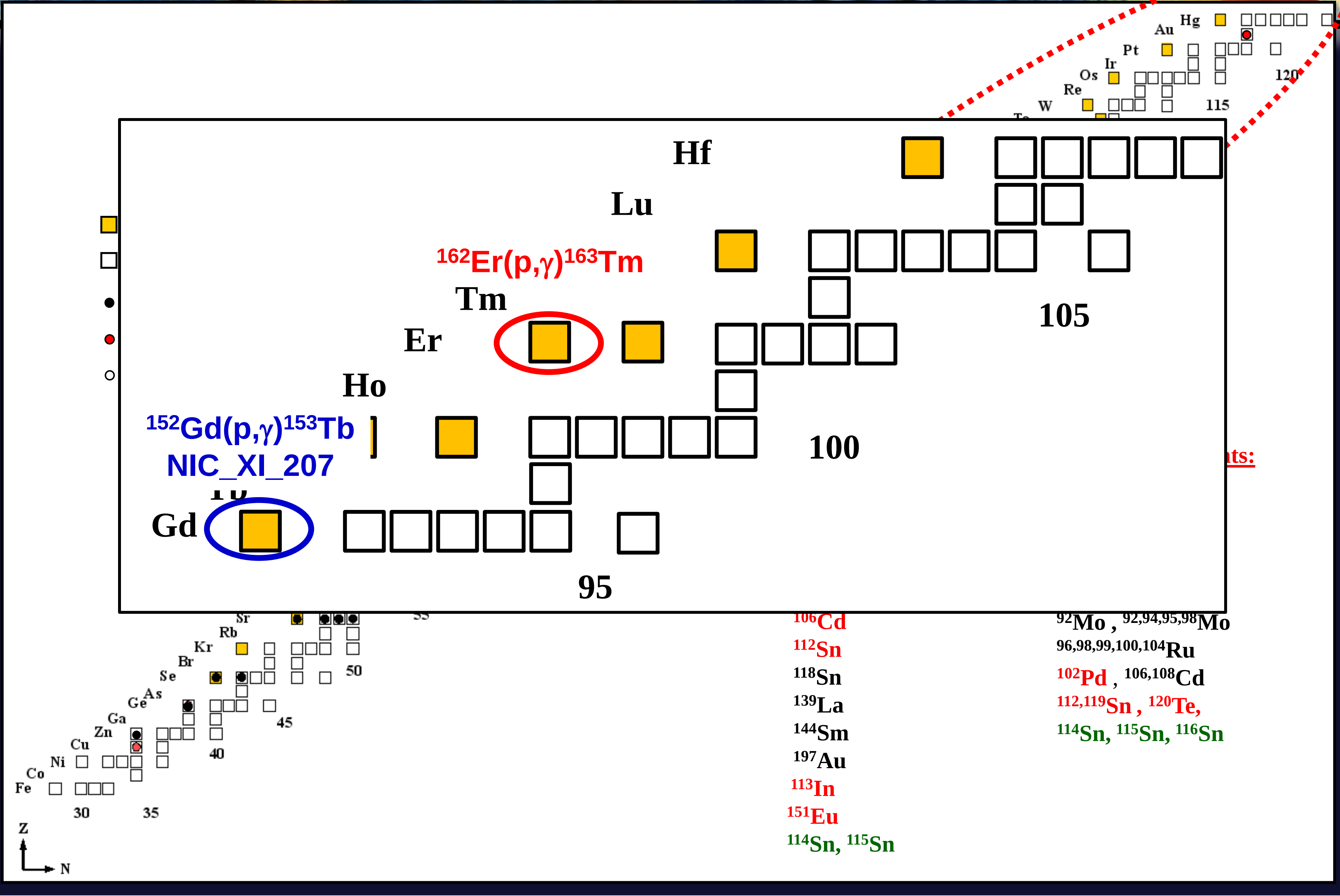
^{63}Cu
^{91}Zr
^{92}Mo
^{96}Ru
^{106}Cd
^{112}Sn
^{118}Sn
^{139}La
^{144}Sm
^{197}Au
^{113}In
^{151}Eu
^{114}Sn, ^{115}Sn

(p,γ) measurements:

^{64}Zn
^{70}Ge, ^{74,76}Se
^{84,86,87}Sr , ^{88}Sr
^{89}Y, ^{90}Zr , ^{96}Zr
^{92}Mo , ^{92,94,95,98}Mo
^{96,98,99,100,104}Ru
^{102}Pd , ^{106,108}Cd
^{112,119}Sn , ^{120}Te,
^{114}Sn, ^{115}Sn, ^{116}Sn

Özkan N. – Nuclei in the Cosmos – IX , CERN, Geneva, Switzerland,, 2006

Experimental measurements by activation method



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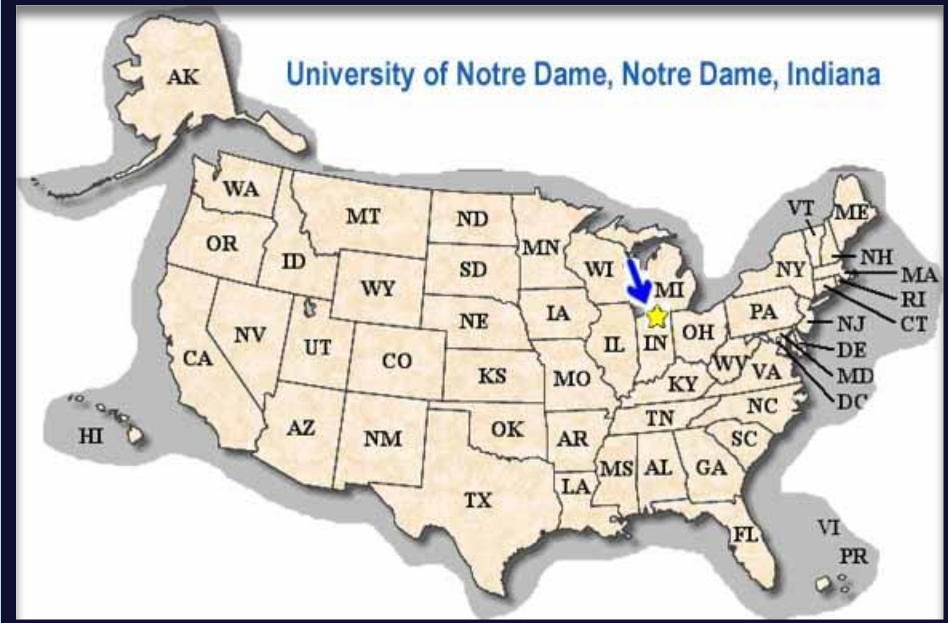


Notre Dame Campus, South Bend, Indiana

3 accelerators + ☺
(JN – 1MV, KN – 4 MV, FN Tandem – 12 MV)

Astrophysics, nuclear structure and reactions, RNB
(radioactive nuclear beams)

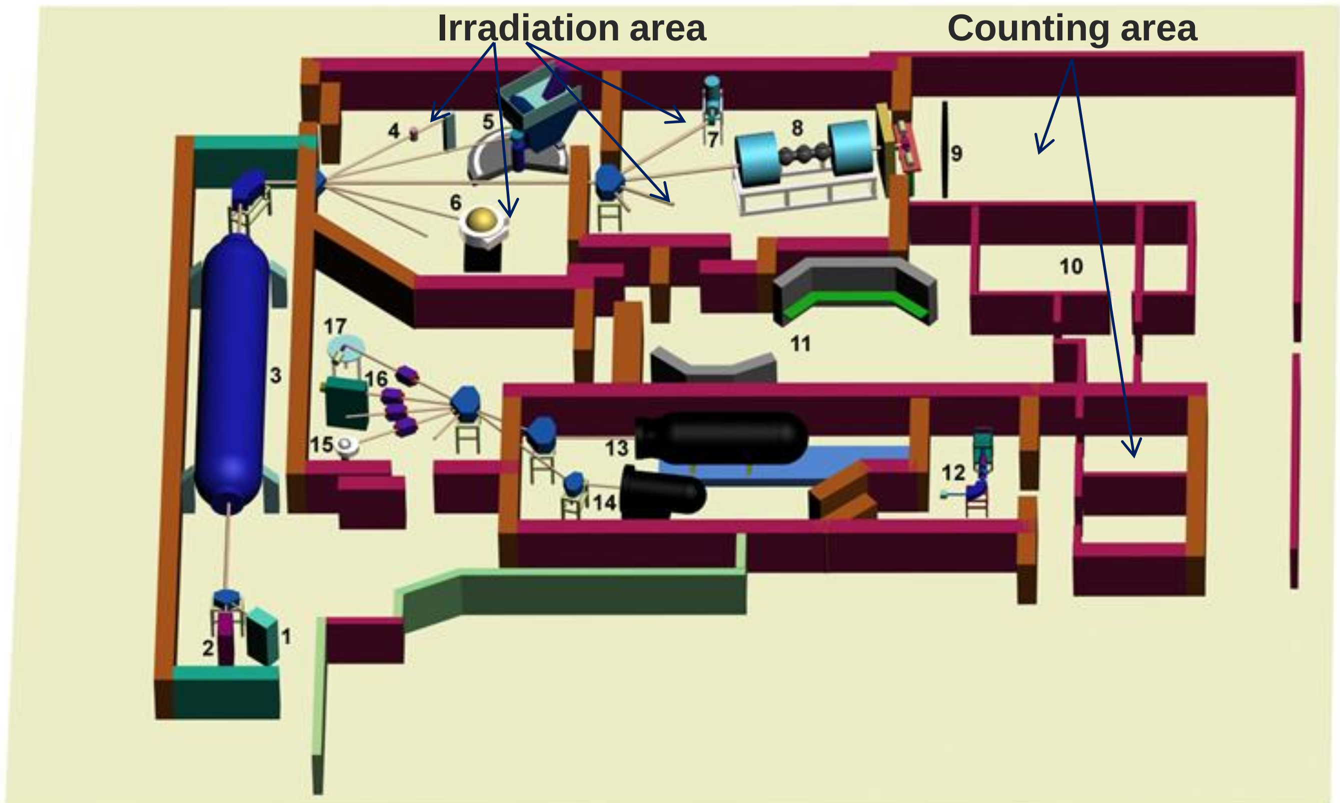

M. Wiescher


J. Görres

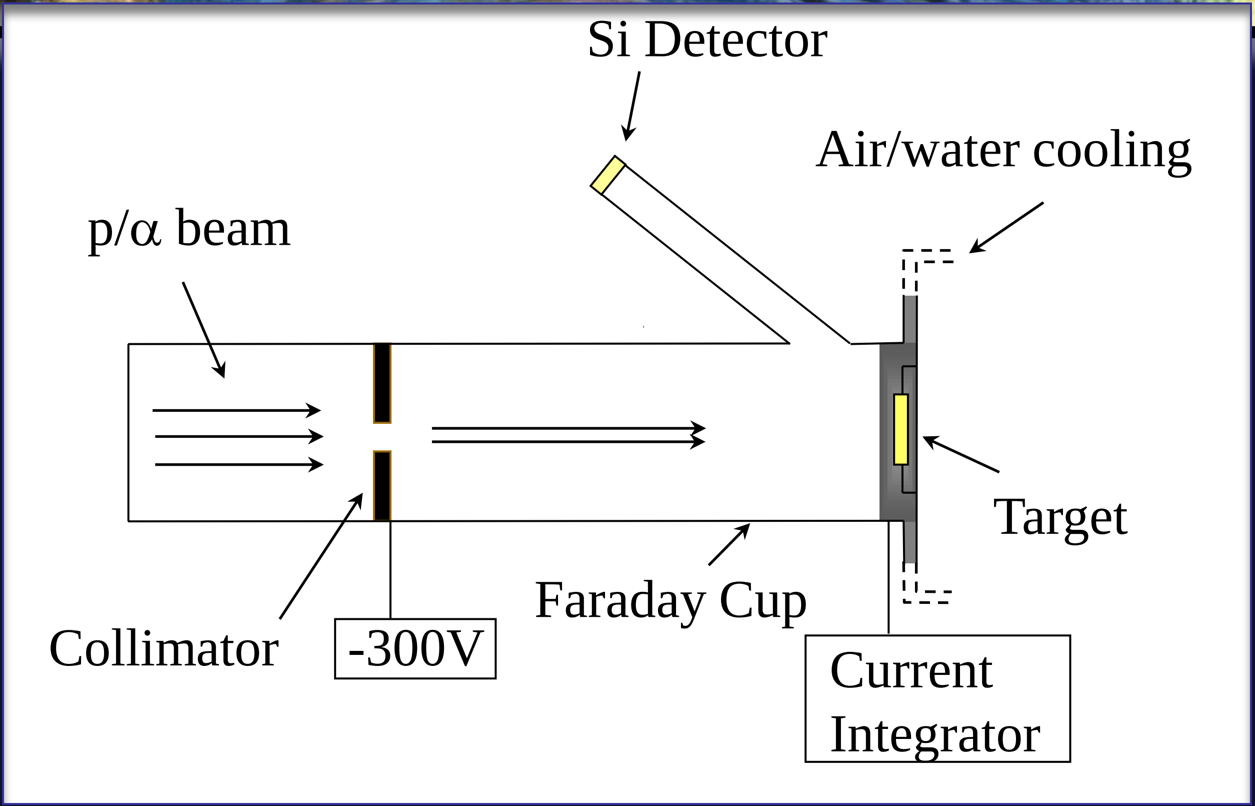

W. Tan

Nuclear Science Laboratory, University of Notre Dame

1. SNICS Ion Source
2. HIS Ion Source
3. FN Van de Graaff Accelerator
4. Gamma Spectroscopy Beamline
5. Spectrograph Beam Line
6. R2D2 Beam Line (1 m scattering chamber)
7. Weak Interaction Beam Line
8. RNB Beam Line
9. Neuton Detection Wall
10. Conference Room
11. Accelerator Control Consoles
12. ECR Ion Source Test Setup
13. KN Van de Graaff Accelerator
14. JN Van de Graaff Accelerator
15. ORTEC Scattering Chamber
16. Windowless Gas Target Beam Line
17. Gamma Table



Activation Setup



Energy range from ~ 4 MeV to 9 MeV

Enriched targets

8 Evaporated targets on C backings: 70-130 $\mu g/cm^2$

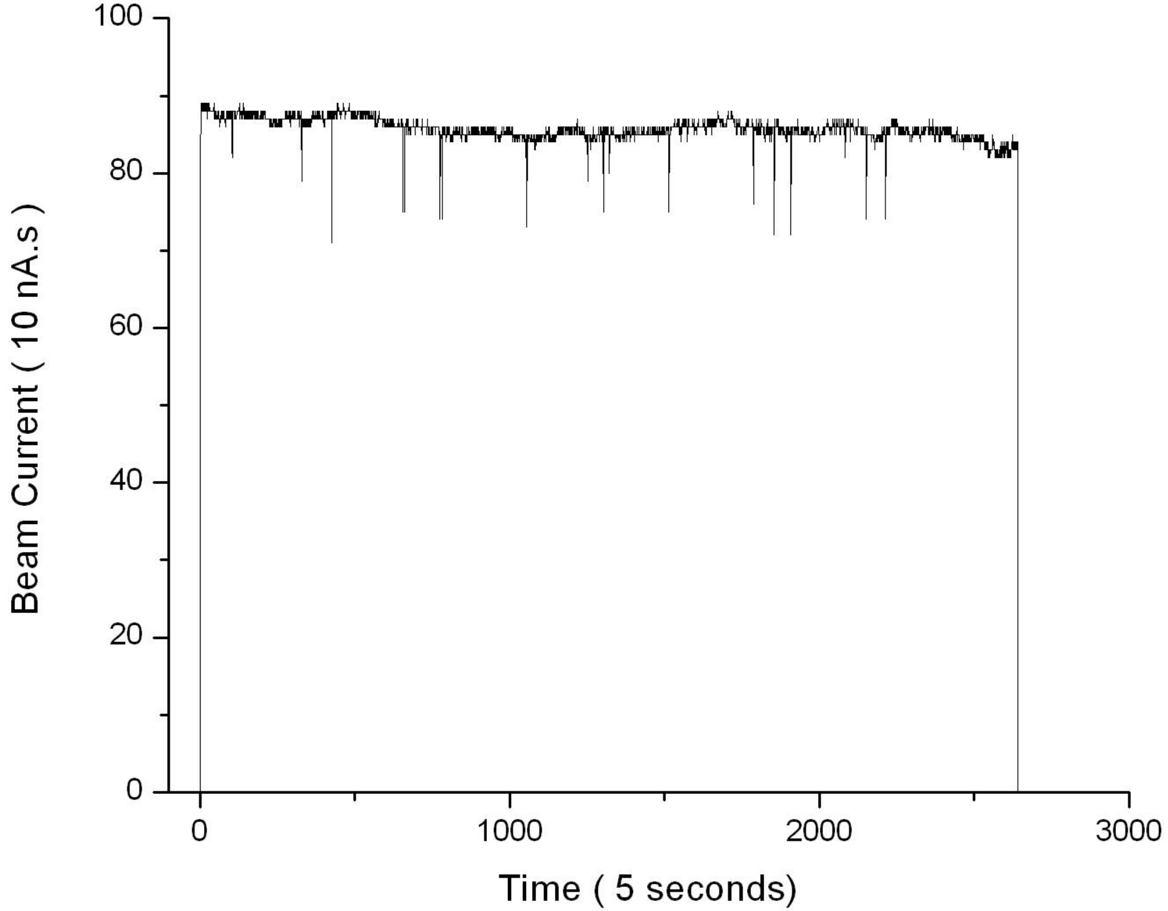
Beam current : 70-300 nA

Target stability monitored with RBS during the irradiation

The beam current was recorded with a current integrator

Beam Current Profile

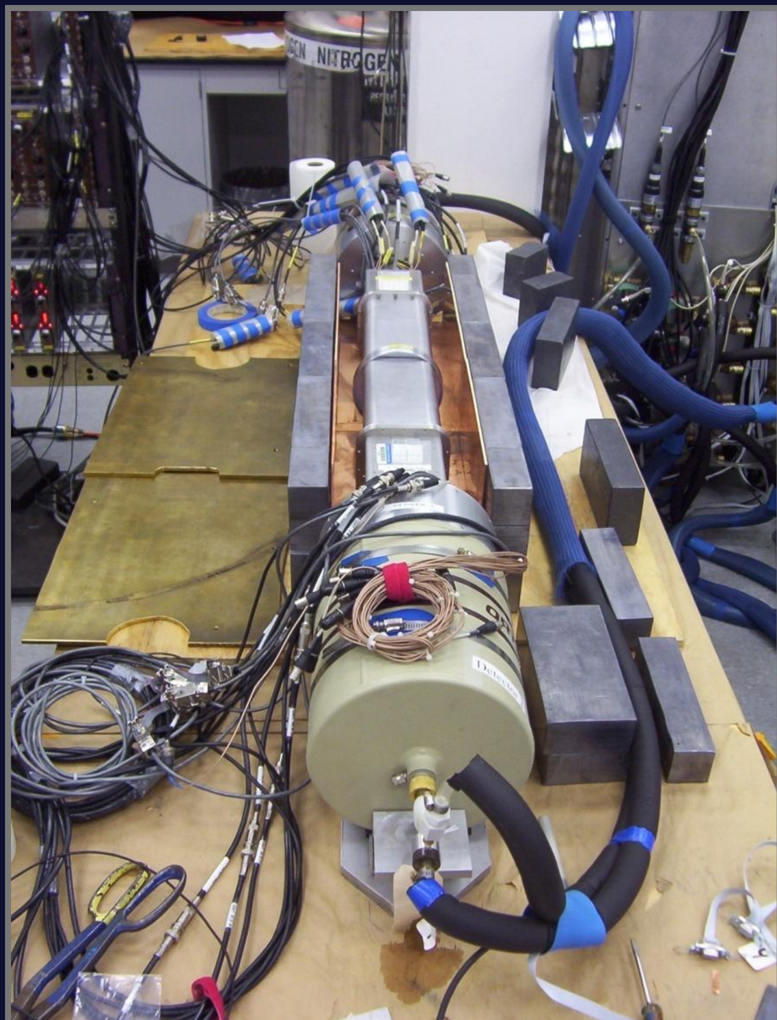
E_p = 5 MeV   I = ~180 nA t_{irr} = ~ 4 h



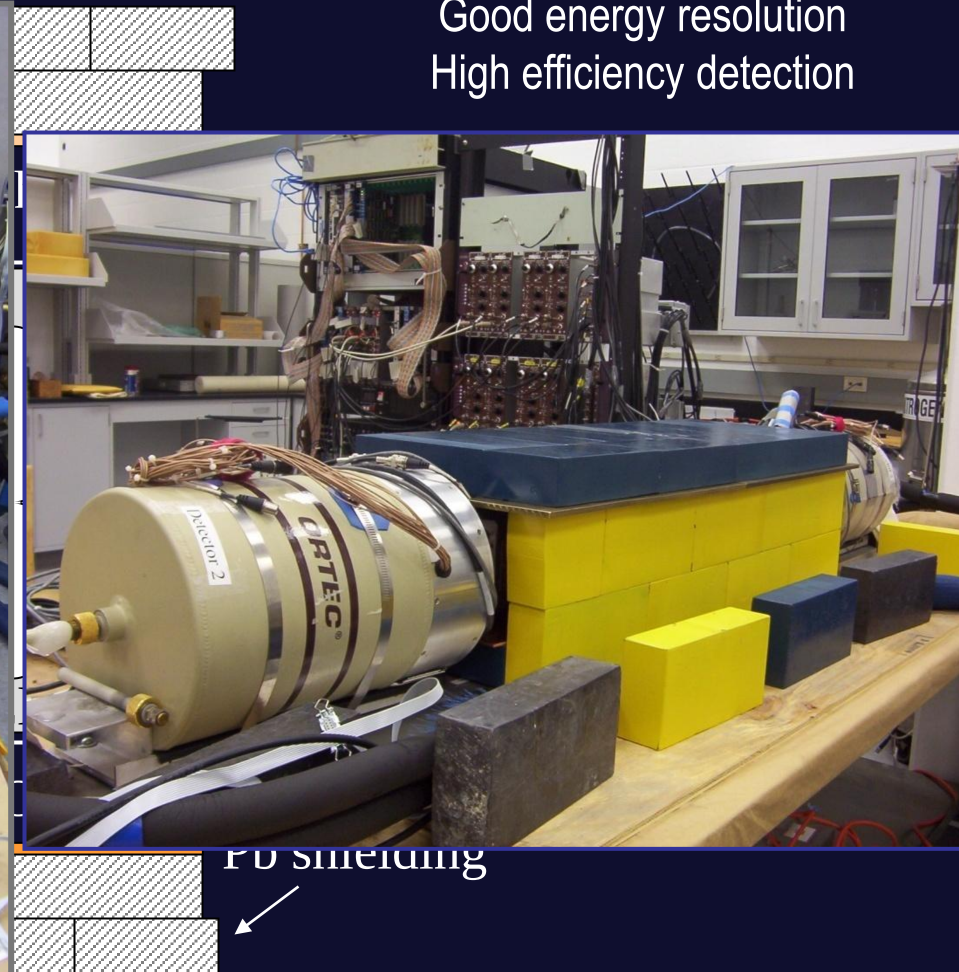
Changes in the current were taken into account in the analysis

Counting Setup

Good energy resolution
High efficiency detection

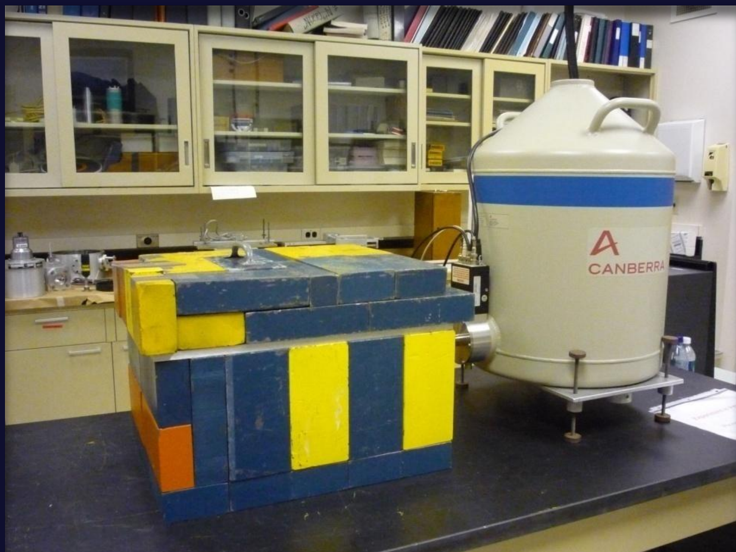


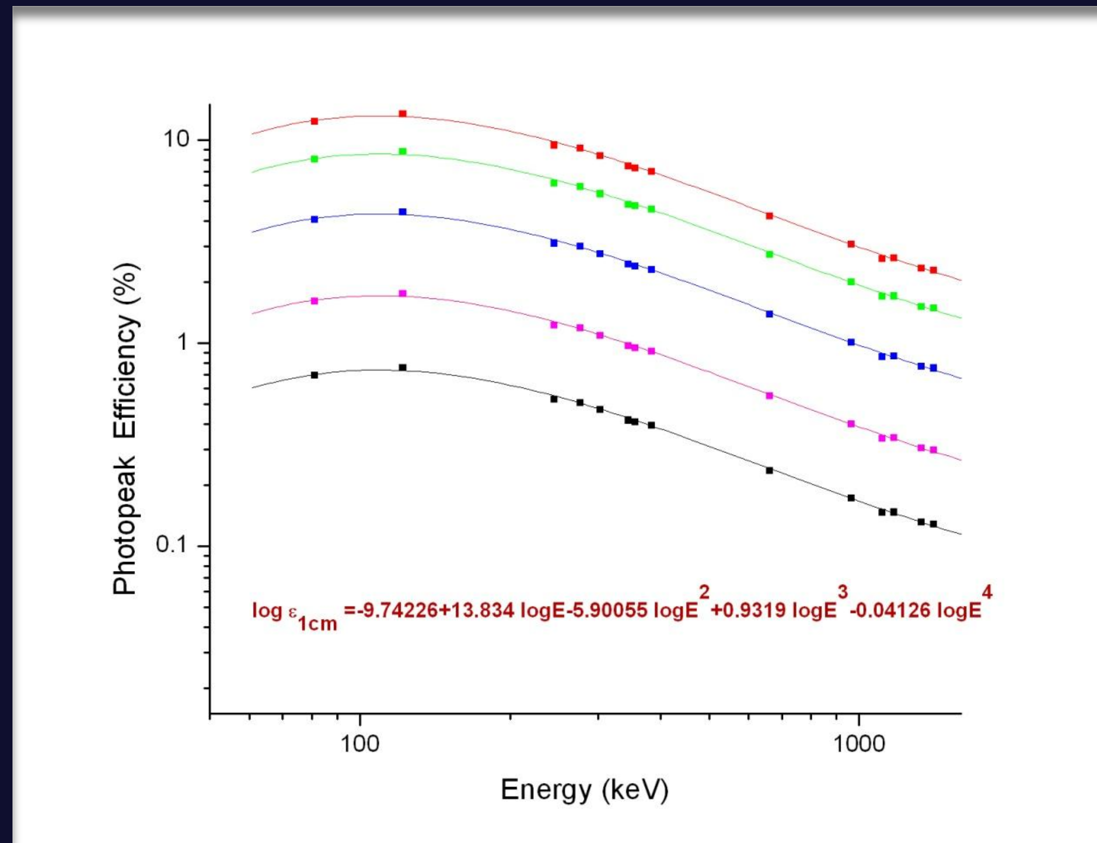
(a)



(b)

Counting Setup





Proton capture reactions of Lantanides

	(p,γ)	(p,n)
Ce-136	***1.28h*** 353.69 (0.58%)- 433.89(1.28%)-- ***9h*** 447.15(1.68%) 436.59(0.25%)	***13.1min*** 461.0 (7.7 %) -539.75 (52.4 %)- 552.16 (76 %) -1092.3(18.5 %)
Ce-138	***4.41h*** 255.11 (0.236 %) -1347.33 (0.47 %)-- ***137.64d*** 165.86 (80 %)	***1.45min*** 788.7 (2.4 %)
Gd-152	***2.34d*** 212 (31 %)-109.76 (6.8%)-102.26 (6.4 %)	***17.5h*** 271.08 (8.6 %)-344.28 (65 %)-586.29 (9.4 %) ***4.2min*** 344.26 (20.1%)- 411.1 (18.2 %)
Gd-154	***5.32d*** 86.55 (32%)-105.32 (25.1%)-262.27 (5.3%)	***21.5h*** 123.07 (26 %)-557.60 (5.4 %)-722.12 (7.7 %)-1274.44 (10.5 %)
Dy-156	***12.6min*** 279.97 (22.7 %) - 341.16(7.5 %) - 896.6 (4 %)	***56min*** no gamma
Dy-158	***33.05min*** 121.01 (36.2 %) 131.97 (23.6 %)- 252.96 (13.7 %) 309.59 (17.2 %)- 838.63 (3.84 %)	***11.3min*** 218.20 (67.1 %) -847.27 (22.5 %) -850.50 (14.3 %) -945.61 (25 %)-1790.62 (15.7 %)
Er-162	***1.81h*** 69.23 (11.6 %)-104.32 (18.6 %)- 241.31 (10.9 %)—***75min***	***21.7min*** 102.00(17.5 %)-227.5 (7 %)-798.68(8.4 %)
Er-164	***30.06 h*** 242.92 (35.5 %)----***10.36h*** no gamma	***2min*** 91.41 (6.7 %)- 208.04 (1.17 %)
Er-166	***9.25d*** 207,8 (42 %)	***7.70h*** 80.59 (11.5 %)-184.41 (16.2 %)- 705.33 (11.1%)-778.81 (19.1 %)-785.9 (10 %) 1273.54 (15.0 %)

Reactions on ^{162}Er isotope

(p,γ) and (p,n) reaction cross sections can be determined simultaneously in the same measurements

Z	160Yb 4.8 M ε: 100.00%	161Yb 4.2 M ε: 100.00%	162Yb 18.87 M ε: 100.00%	163Yb 11.05 M ε: 100.00%	164Yb 75.8 M ε: 100.00%	165Yb 9.9 M ε: 100.00%	166Yb 56.7 H ε: 100.00%	167Yb 17.5 M ε: 100.00%	168Yb STABLE 0.13%
69	159Tm 9.13 M ε: 100.00%	160Tm 9.4 M ε: 100.00%	161Tm 30.2 M ε: 100.00%	162Tm 21.70 M ε: 100.00%	163Tm 1.810 H ε: 100.00%	164Tm 2.0 M ε: 100.00%	165Tm 30.06 H ε: 100.00%	166Tm 7.70 H ε: 100.00%	167Tm 9.25 D ε: 100.00%
68	158Er 2.29 H ε: 100.00%	159Er 36 M ε: 100.00%	160Er 28.58 H ε: 100.00%	161Er 3.21 H ε: 100.00%	162Er STABLE 0.139%	163Er 75.0 M ε: 100.00%	164Er STABLE 1.601%	165Er 10.36 H ε: 100.00%	166Er STABLE 33.503%
67	157Ho 12.6 M ε: 100.00%	158Ho 11.3 M ε: 100.00%	159Ho 33.05 M ε: 100.00%	160Ho 25.6 M ε: 100.00%	161Ho 2.48 H ε: 100.00%	162Ho 15.0 M ε: 100.00%	163Ho 4570 Y ε: 100.00%	164Ho 29 M ε: 60.00% β-: 40.00%	165Ho STABLE 100%
66	156Dy STABLE 0.06%	157Dy 8.14 H ε: 100.00%	158Dy STABLE 0.10%	159Dy 144.4 D ε: 100.00%	160Dy STABLE 2.34%	161Dy STABLE 18.91%	162Dy STABLE 25.51%	163Dy STABLE 24.90% β-: 100.00%	164Dy STABLE 28.18%
	90	91	92	93	94	95	96	97	N

(p,n)
(p,γ)
β+

6 stable isotopes of Erbium - Enriched isotopes are needed!

*www.nndc.bnl.gov/**nudat**2/*

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CERTIFICATE of ANALYSIS

CUSTOMER:

University of Notre Dame
Attn: Dr. Nalan Guray
124/Physics CR1
Nieuland Science Center
116 Maintenance Center, Building NIEU
Notre Dame, IN 46556-5688
Tel: 574-631-8204

CERTIFICATE NO.: 68-02-162-1177

CUSTOMER ORDER NO.: Per Dr. Guray's emails dated June 2, 2009

The description, isotopic distribution and chemical admixtures relating to the above referenced order number are certified to be as follow:

Description

ISOTOPE	Er-162
ENRICHMENT	28.80%
ELEMENT WEIGHT	40 mg
FORM	Oxide (Er_2O_3)

Isotopic Distribution

ISOTOPE	Er-162	Er-164	Er-166	Er-167	Er-168	Er-170
CONTENT (%)	28.2	7.41	32.24	14.26	12.26	5.63

Chemical Admixtures

ELEMENT	K	Na	Ca	Mg	Fe	Si	Al	Cr	Cu	Pb
CONTENT (%)	0.004	<0.002	0.005	0.004	<0.005	0.005	<0.005	0.03	<0.005	<0.005

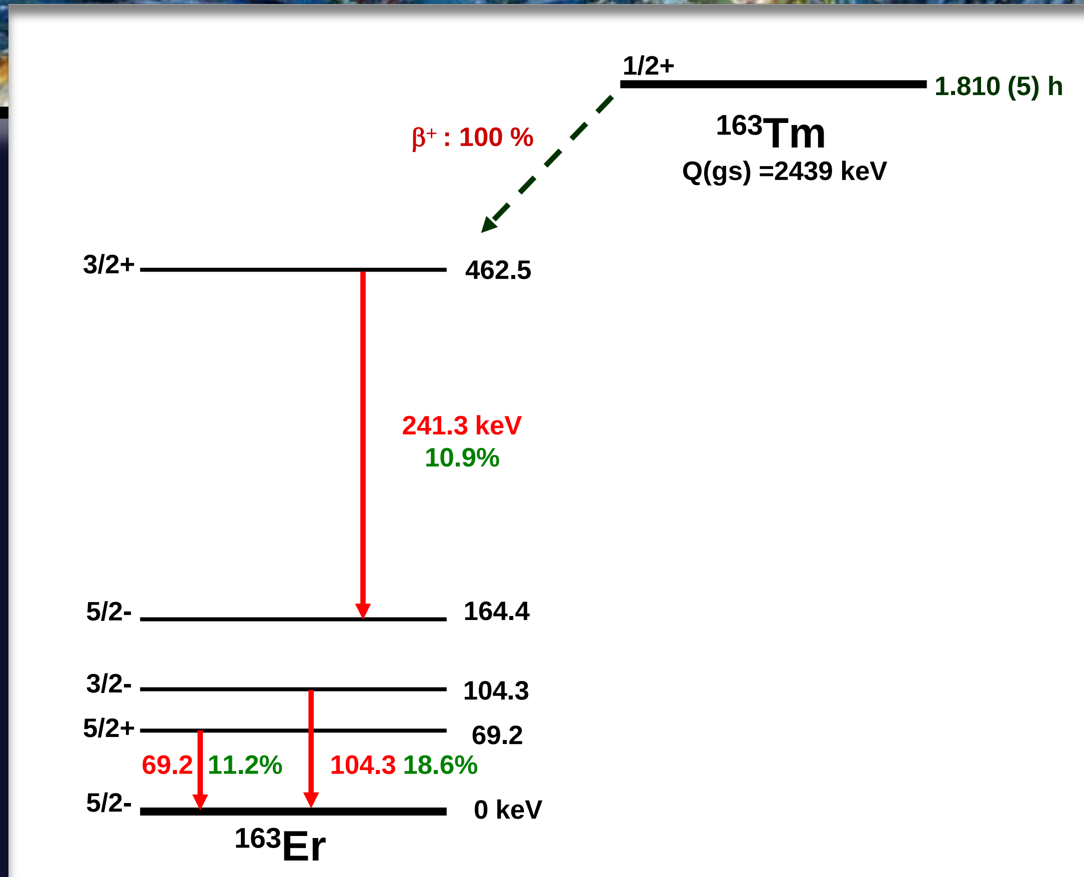
ELEMENT	Sn	Gd	Tb	Dy	Ho	Yb	Tm	Lu
CONTENT (%)	0.02	0.06	0.06	0.11	<0.1	<0.04	<0.05	<0.06

Impurities in the target (higher half-lives)

Isotopic distribution	(p,γ) Gamma Energies in keV ($I\gamma$%)	(α,γ)
^{162}Er(28.2%)	***1,81h*** 69.23 (11.6%)-104.32 (18.6%) 241.31 (10.9%) --***75m*** no gammas-- ***4570y*** 299 (77.9%)	***56.7h*** 82.29 (15.55%)-- ***7.70h*** 80.585 (11.5%) -184.41 (16.2 %) -778.81 (19.1%)
^{164}Er (7.41%)	***30.06h*** 242.92(35.5%)- 297.40(12.71%)→ ***10.36h*** no gammas	X
^{166}Er (32.24%)	***9.25d*** 207 (42%)	X
^{167}Er (14.26%)	***93d*** 79.8 (10.8%)-184.3 (17.9%)-198.3 (53%)- 447.51 (23.7%)-720.4 (12%)	X
^{168}Er (12.26%)	X	X
^{170}Er (5.63%)	X	X

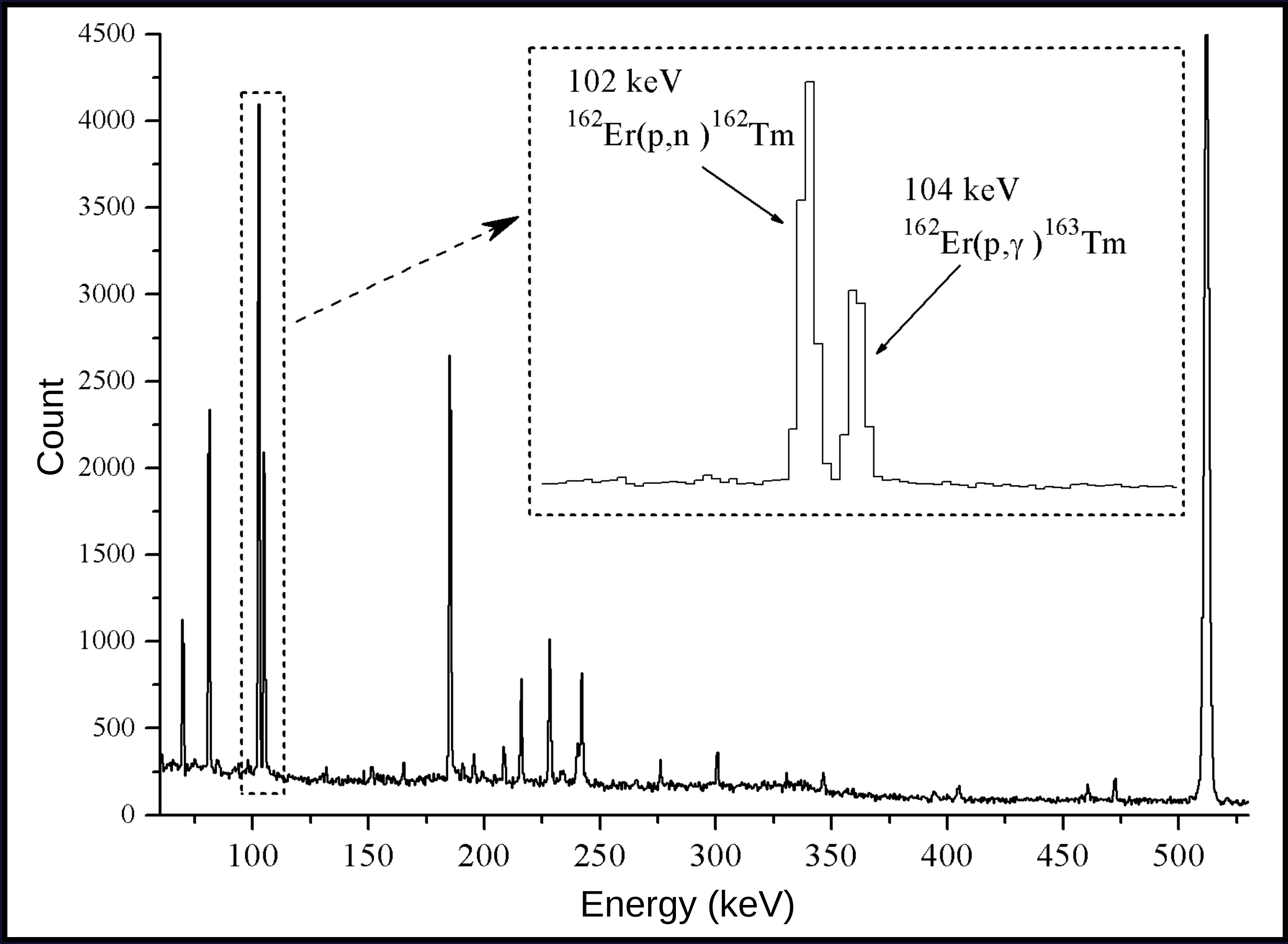
Made our lives easier!

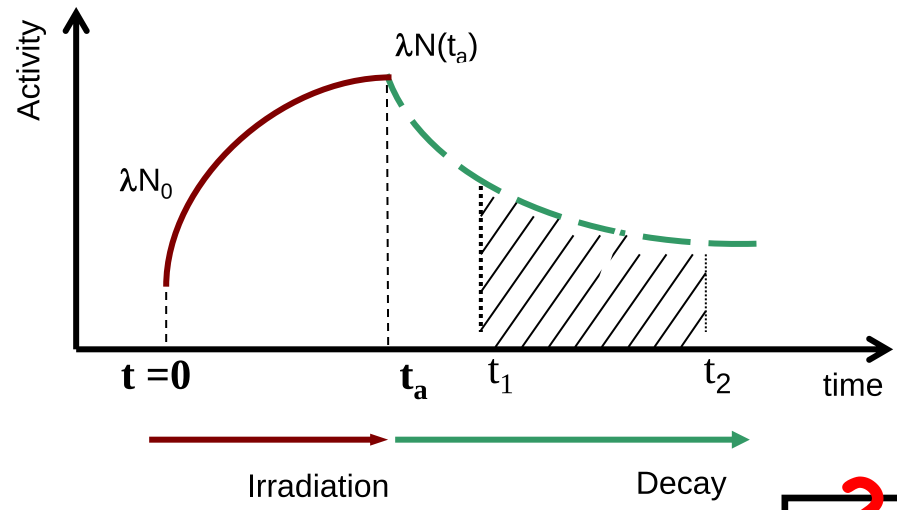
$^{162}Er(p,\gamma)^{163}Tm \rightarrow {}^{163}Er \rightarrow {}^{166}Ho \rightarrow {}^{163}Dy$ (stable)



Reaction	Product	Half-life	γ-Energy (keV)	γ- Intensity (%)
$^{162}Er(p,\gamma)$	^{163}Tm	(1.81±0.05) h	69.23	11.6±0.3
			104.32	18.6±0.4
			241.31	10.9 ±0.3
$^{162}Er(p,n)$	^{162g}Tm	(21.70±0.19) min	102.00	17.57±0.07

Gamma Spectrum at 7 MeV for 30 minutes irradiation and 165 minutes counting





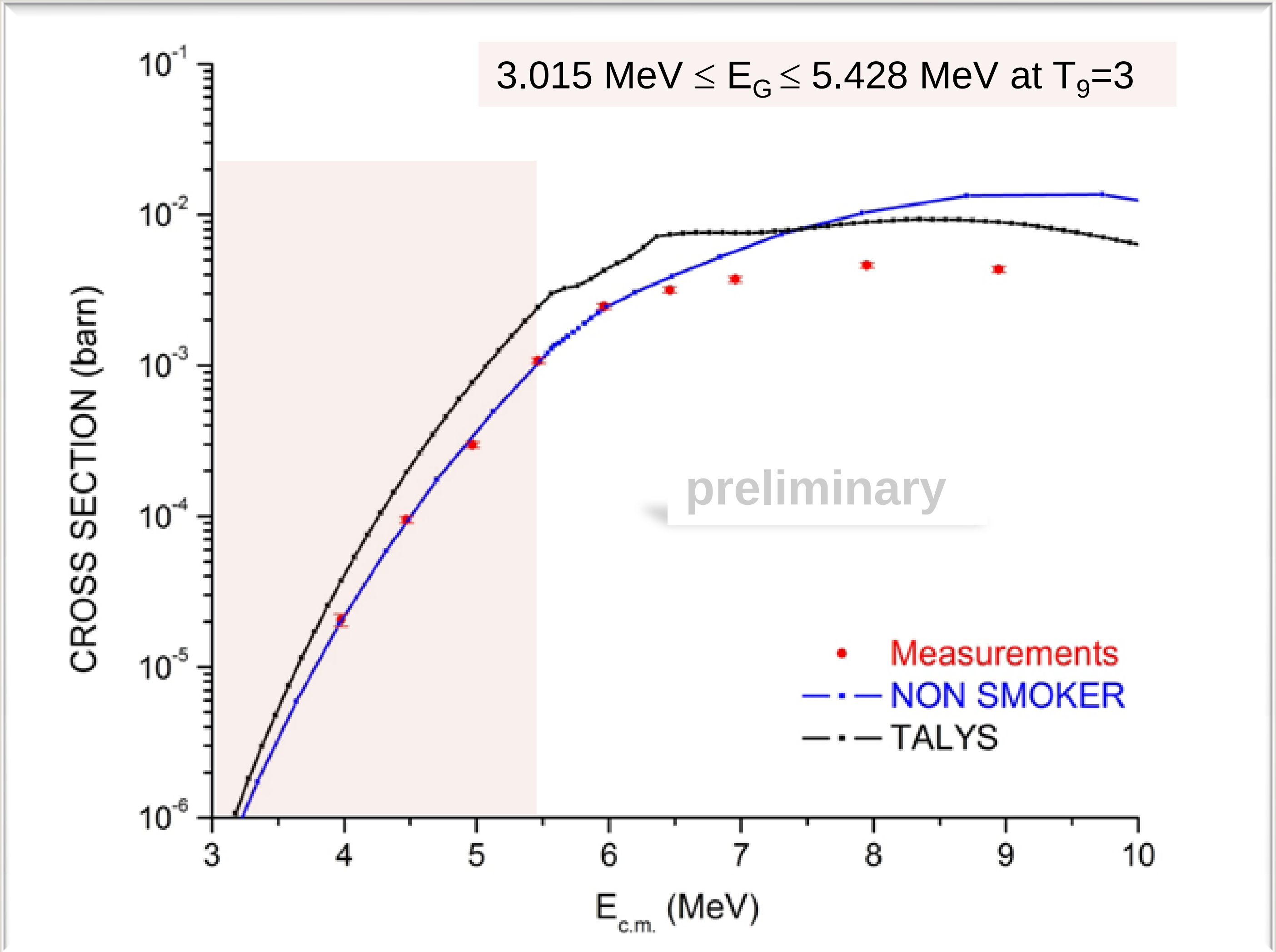
$$a + A \longrightarrow B + \gamma$$

$$N_B(t_a) = \frac{\sigma \, n_t \, \phi}{\lambda_B}\left(1 - e^{-\lambda_B t_a}\right) + N_{B0}\, e^{-\lambda_B t_a}$$

$$N_{decay} = N_B(t_a)\left(e^{-\lambda_B t_1} - e^{-\lambda_B t_2}\right)$$

$$N_{decay} = \frac{Ncount \quad C}{I\gamma \;\; t \;\; \varepsilon}$$

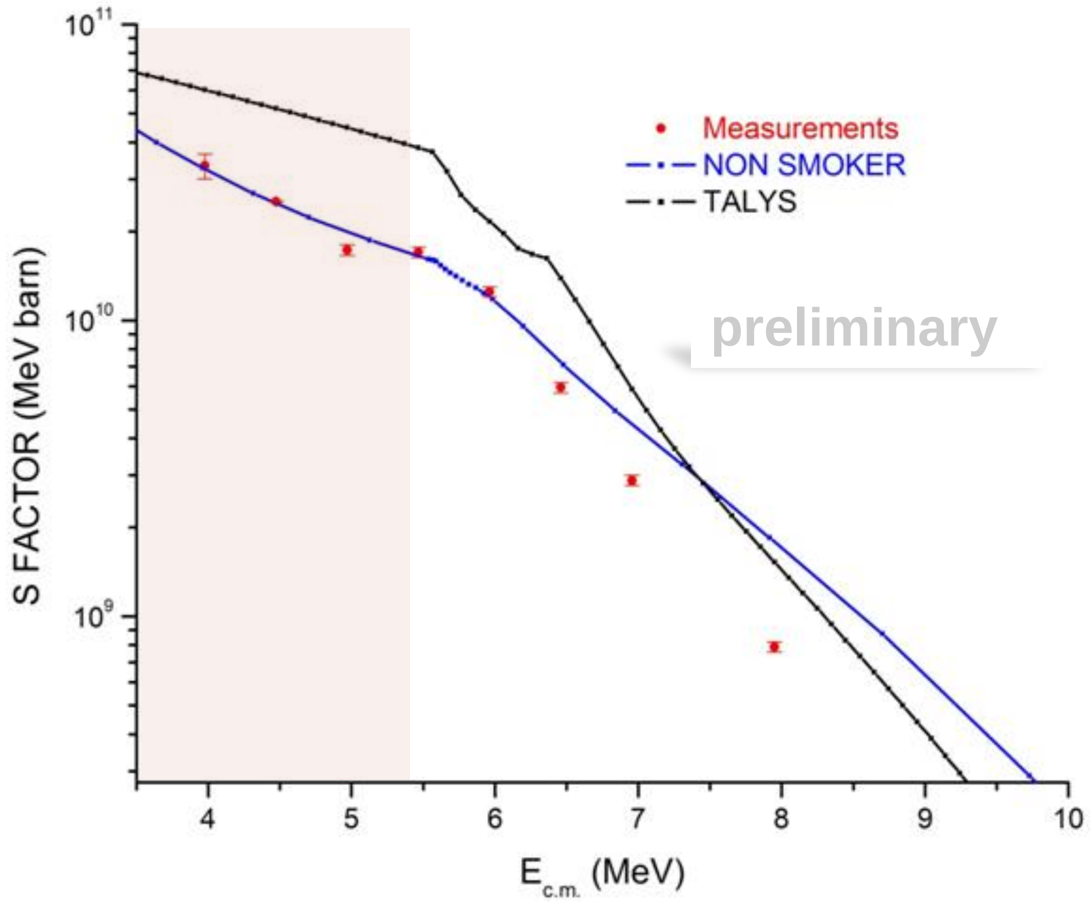
Comparision of the measured Cross Sections and the HF statistical model calculations for $^{162}Er(p,\gamma)^{163}Tm$



NS/Measurements : 0.6-3.1
TALYS/Measurements:1.7-2.5

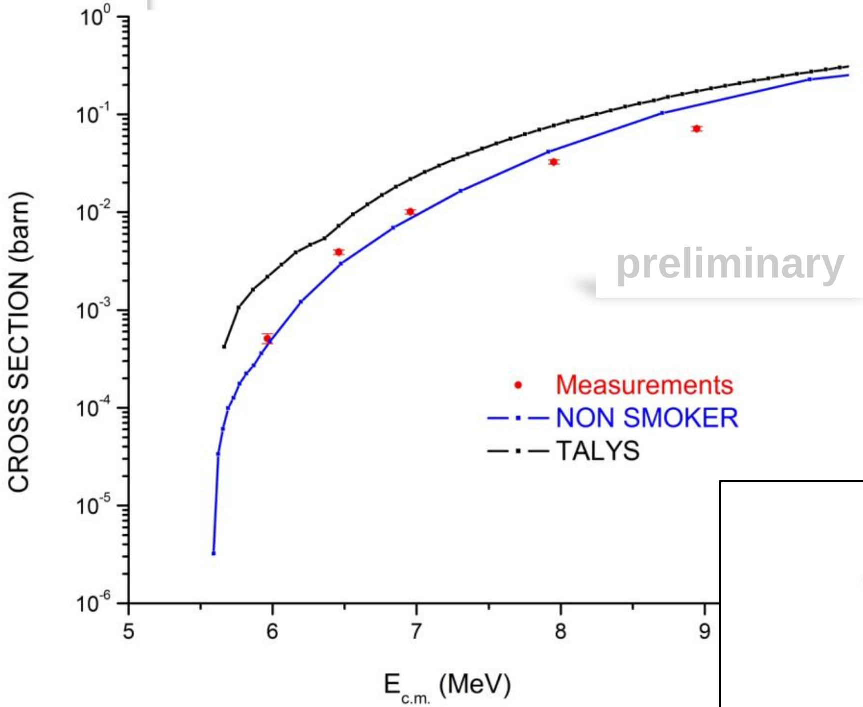
http://nucastro.org/reaclib.html
http://www.talys.eu

S factor $^{162}Er(p,\gamma)^{163}Tm$



- counting statistics : 1 % - 5 %
- detection efficiency : **3 %**
- decay parameters : less than 3 %
- target thickness : 9 **%**
- beam energies : % 0,02 - % 0,5

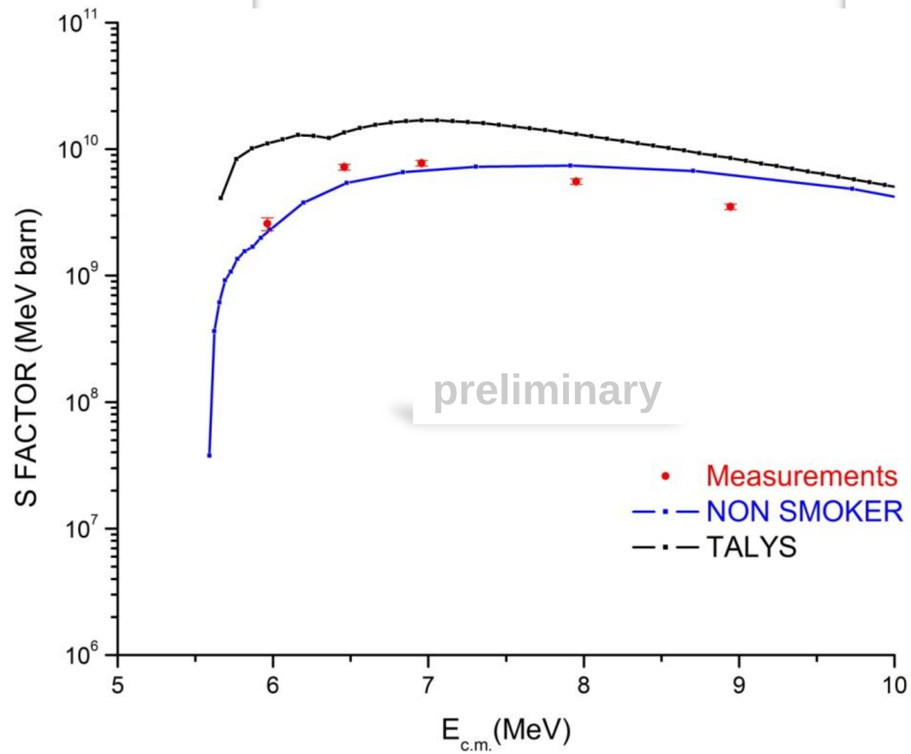
Cross Section $^{162}Er(p,n)^{162}Tm$



NS/Measurements : 0.9-1.45

TALYS/Measurements: 0.13-8.4

S-factor $^{162}Er(p,n)^{162}Tm$



The final results are going to be compared to the NON-SMOKER results with different input parameters!

Acknowledgement

- Joint Institute for Nuclear Astrophysics (JINA)
- The Scientific and Technical Research Council of Turkey TUBİTAK : TBAG-108T508
- Hungarian Scientific Research Fund OTKA
- Kocaeli University BAP: 2007/36
- Our Collaborators

This is the early announcement for a p-process workshop taking place in Istanbul
Supported by ***JINA*** (Joint Institute for Nuclear Astrophysics)

Contact: Nalan Özkan
Email : nozkan@kocaeli.edu.tr

Thank you for your attention!

http://apod.nasa.gov/apod/ap100615.html

Starry Night Scavenger Hunt

Credit & Copyright : *Original Painting:* Vincent van Gogh; *Digital Collage:* Ronnie Warner

Explanation: Did you know that Van Gogh's painting Starry Night includes Comet Hale-Bopp?

Hopefully not, because it doesn't. But the above image does. Although today's featured picture may appear at first glance to be a faithful digital reproduction of the original Starry Night, actually it is a modern rendition meant not only to honor one of the most famous paintings of the second millennium, but to act as a scavenger hunt.

Can you find, in the above image, a comet, a spiral galaxy, an open star cluster, and a supernova remnant? Too easy? OK, then find, the rings of Supernova 1987A, the Eskimo Nebula, the Crab Nebula, Thor's Helmet, the Cartwheel Galaxy, and the Ant Nebula.

Still too easy?
Then please identify any more hidden images not mentioned here -- and there are several – on APOD's main discussion board: Starship Asterisk.

Finally, the collagist has graciously hidden APOD's 10th anniversary Vermeer photomontage to help honor APOD on its 15th anniversary tomorrow.